

ADAPTIVE SPACE STRUCTURES

Introduction

Adaptive structures. The term *adaptive structures* refers to a structural control approach in which sensors, actuators, electronics, materials, structures, structural concepts, and system-performance-validation strategies are integrated to achieve specific objectives. Adaptive structures' geometric and inherent structural characteristics can be changed beneficially in response to external stimulation either by remote commands or automatically. Among the advantages of incorporating adaptive structures are the savings that result from the lower costs associated with cheaper materials, fabrication, thermal control, analysis, and testing. Adaptive structures do not require the same initial degree of precision as passive systems, because the ability to adjust the system while it is operating can compensate for uncertainties. Also, because the structure itself places fewer demands on the control system, the requirements for controls can be decreased. Currently researchers are integrating several of the elements of adaptive structures and establishing measures of performance through ground test, analysis, and experimentation.

Structural control approaches. Figure 1 illustrates the breadth of structural control approaches. The two basic categories are *sensory* structures, whose sensors determine or monitor system states or characteristics, and *adaptive* structures, whose actuators alter system states or characteristics in a controlled manner (such as robotics or a deployable structure). A sensory system might have sensors for health monitoring but no actuators. Conversely, an adaptive system might have actuators for a controlled deployment but no sensors. The intersection of sensory and adaptive structures is *controlled* structures, with both sensors and actuators in a feedback architecture for the purpose of actively controlling system states or characteristics.

Controlled structures include *active* structures and *intelligent* structures. Active structures are controlled with sensors or actuators (or both) that are highly integrated and have both structural and control functionality. Their hybrid nature characterizes the truly integrated control/structural system. The terms adaptive structures and active structures are often used interchangeably. Intelligent structures contain highly integrated control logic and electronics that provide the ability to learn and respond to new situations.

Using Adaptive Structures in Space

Benefits. A structure in space may require structural changes to initially establish the desired configuration and characteristics, to maintain the desired configuration and characteristics during its operational life in space, to change its characteristics as required to adapt to different events, and to respond to external and internal stimulations. "The adaptive structures approach is especially suited for space applications because it supports these capabilities as well as requirements for the system to operate remotely for as many as 30 years without the opportunity for subsequent modifications or adjustment. Adaptive structures technology can be used to build large (20 to 30 meters in dimension) space structures with submicron precision for space observations (e. g., Figure 2) and promises to

reduce cost and improve reliability on smaller and less demanding structures. Adaptive structures technology provides the opportunities for designers to introduce "robustness" into the design, rather than imposing stringent controls on design, analysis, fabrication, and testing, while increasing reliability to meet the requirements. More specifically, significant structural reliability and performance improvements in ground validation tests, deployment, reducing structural nonlinearities, in-space system identification, quasi-static adjustments, dynamic adjustments, and increased structural reliability are feasible.

Actuators and sensors for space structures. Adaptive structures became feasible as the sensitivity of sensors and actuators approached the displacement and force levels associated with precision structures. The current actuator materials of choice for space applications are piezoelectric, electrostrictive, or possibly magnetostrictive because of their precision submicron displacement resolution and frequency bandwidth. Other thermally activated actuator materials, such as shape memory alloy and thermal wax pellet,² provide longer stroke actuation, but their frequency responses are less than a few hertz and they are only used in designs requiring actuation at one physical location. For most materials, small displacement changes and large changes in the damping values of viscoelastic materials are feasible by controlling the temperature of the material itself. The viscoelastic properties of electrorheological materials (very fine dielectric particles in an insulating medium) appropriately located within the structure can be varied by applying different levels of electric fields. Sensors of choice include both ceramic and polymer piezoelectric materials as well as noncontact sensors with resolution down to 2 nanometers. Sensors and actuators are typically ~~in~~ bedded into composite materials and are often mounted on the surface of structures. In the near future, the electronics will be miniaturized to allow them to be ~~in~~ bedded in or collocated with the active members.

Space Applications Experiments

Significant progress has been made since 1988 because a realistic system is available for experimental research. The system consists of four large ground test systems, ranging from 5 meters to 17 meters in dimension, that are available at government facilities. Several spaceflight experiments are being developed to validate vibration suppression, system identification, and motion suppression. To support the experiments, efficient electronics and power supplies for adaptive structures are in design. By the end of 1994, several spaceflight experiments and a flight system will be launched into space using adaptive structures. Several examples of structural systems in space are discussed below.

An illustrative example of a structural system that exhibits many features of adaptive structures is a space crane (shown in Figure 3) that may be used in the future to assemble structures in space. Active members incorporated into the crane are used to transfer loads, provide large actuation to deploy and position the crane structure and its tip at various locations, and add damping and change the structural stiffness. The active members are exciters and sensors that identify the crane's dynamic characteristics in different positions of interest, maintain the tip position during temperature changes, and provide redundancy by addition of space active members. The design is robust and alleviates ground test requirements because the system is adjustable in space.

The objective of the vibration disturbance rejection experiment shown in Figure 4 is to hold the position of the optical component to within a 10-nanometer root-mean-square (rms) when the structure is subjected to excitation from the vibration source. The strategy is to reduce the level of the disturbance from the source to the truss structure by using active structures, reduce the vibration transmission through the structure using active members and passive dampers, and then moving the optical elements using small and large displacement actuators. The displacement was reduced by a factor of 5100, and the optical path length was stabilized to 5 nanometers rms.

The objective of the articulating fold mirror of the Wide Field Planetary Camera II is to correct the wavefront error of the Hubble Telescope. The design requirement is for a tip/tilt range of the mirror to be greater than ± 206 arc seconds, with a tilt step size of about 1 arc second. The capability to adapt the angular position of the mirror in space resulted from the uncertainties of maintaining the desired position during its launch into space and its exposure to the space environment. The actuator is a electrostrictive ceramic composed of lead magnesium niobate.

Two active members located within a 12-meter truss structure successfully increased its modal damping values from about 1 percent to 7 percent during a 15-second zero-gravity experiment aboard an experimental KC-135 aircraft flying parabolic trajectories. The value of structural damping was changed on a structure with large uncertainties on its structural dynamic characteristics.

On a 4.5-meter graphite epoxy truss structure, active members placed at strategic locations were successfully used to adjust the location of critical nodes forming the geometry of the circular telescope and to add damping to the structure. Small gaps at the joints that resulted in a nonlinear random response were eliminated by active members.

Long-wavelength errors of a graphite 0.6-meter composite optical hexagonal panel were corrected using piezoelectric actuators mounted to the back surface of the honeycomb structure. Corrections of errors up to 10 microns reduced the surface rms error to less than 2 microns rms.

Future Outlook

Although the concepts of adaptive structures presented in this report emphasize space applications, the ideas are equally valid for many other applications, including shape control of aircraft wings to improve aeroelastic stability; noise attenuation for ships, aircraft, precision machinery and optics; civil structures; automobile ride comfort; helicopter rotor blade vibration suppression; biomedical applications; rotor shaft vibration attenuation; and many commercial products requiring miniaturization such as cameras. Many new actuator materials are being rediscovered and evaluated for these applications. The interest has grown exponentially, as demonstrated by two technical journals, several conferences, technical committees, and sessions at many meetings. Adaptive structures technology promises to provide opportunities to design new and more efficient mechanical systems in all fields of engineering.

References

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Figure captions

Figure 1. Conceptual framework for structural control approaches. The adaptive structures approach (A) is well-suited for space applications because it supports long-term remote operations. (printed previously: Ben K. Wada, James I. Fanson, and Edward F. Crawley, "Adaptive Structures," *Mechanical Engineering*, November 1990.)

Figure 2. Artist's conception of an optical interferometer. Adaptive structures technology would be used to deploy or assemble large truss-type structures such as this in space. (printed previously: Ben K. Wada and John A. Garba, "Advances in Adaptive Structures at Jet Propulsion Laboratory," *Proceedings of the Advisory Group for Aerospace Research & Development (A GARD) Conference 531, Smart Structures for Aircraft and Spacecraft*)

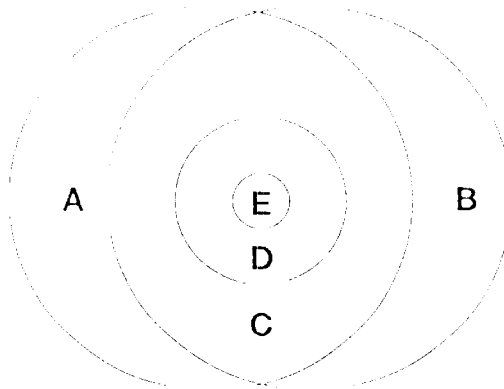
Figure 3. Space crane used as an in-space assembly and construction facility. Adaptive structures technology is used to adjust the space crane in space as needed.

Figure 4. Vibration disturbance rejection experiment, which uses active structures to reduce the level of disturbance from the source to the truss structure.

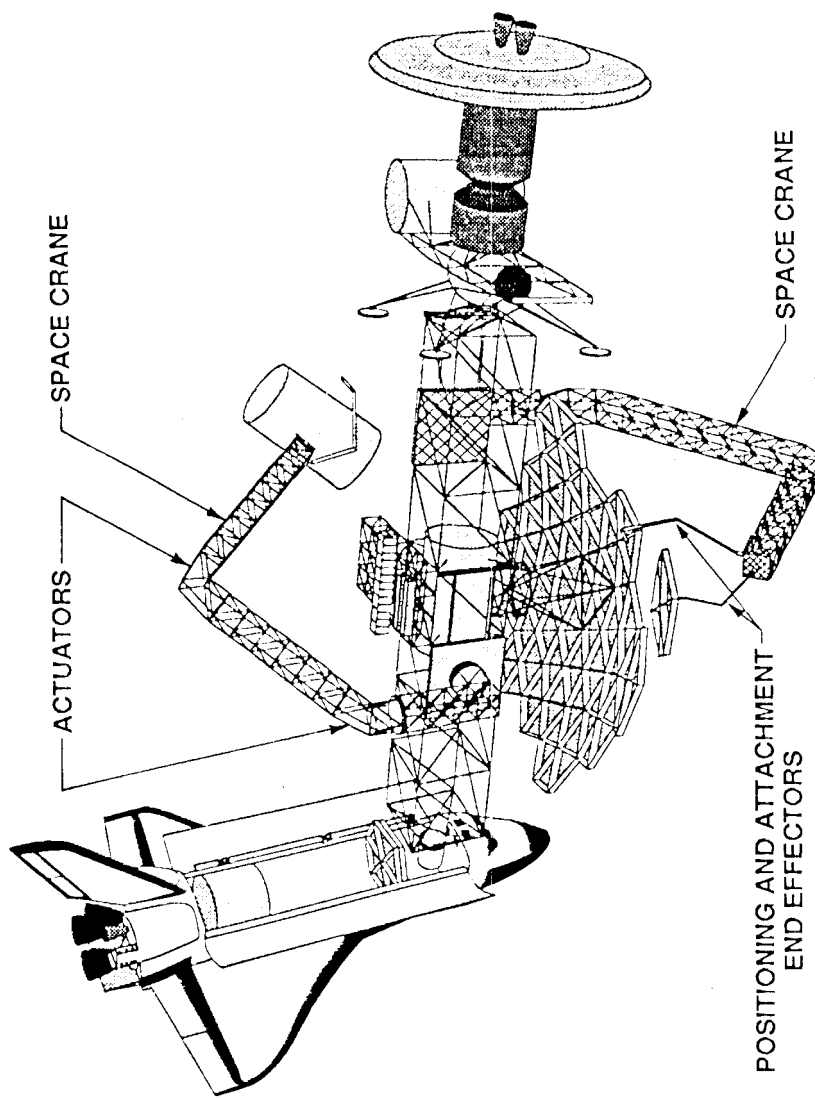
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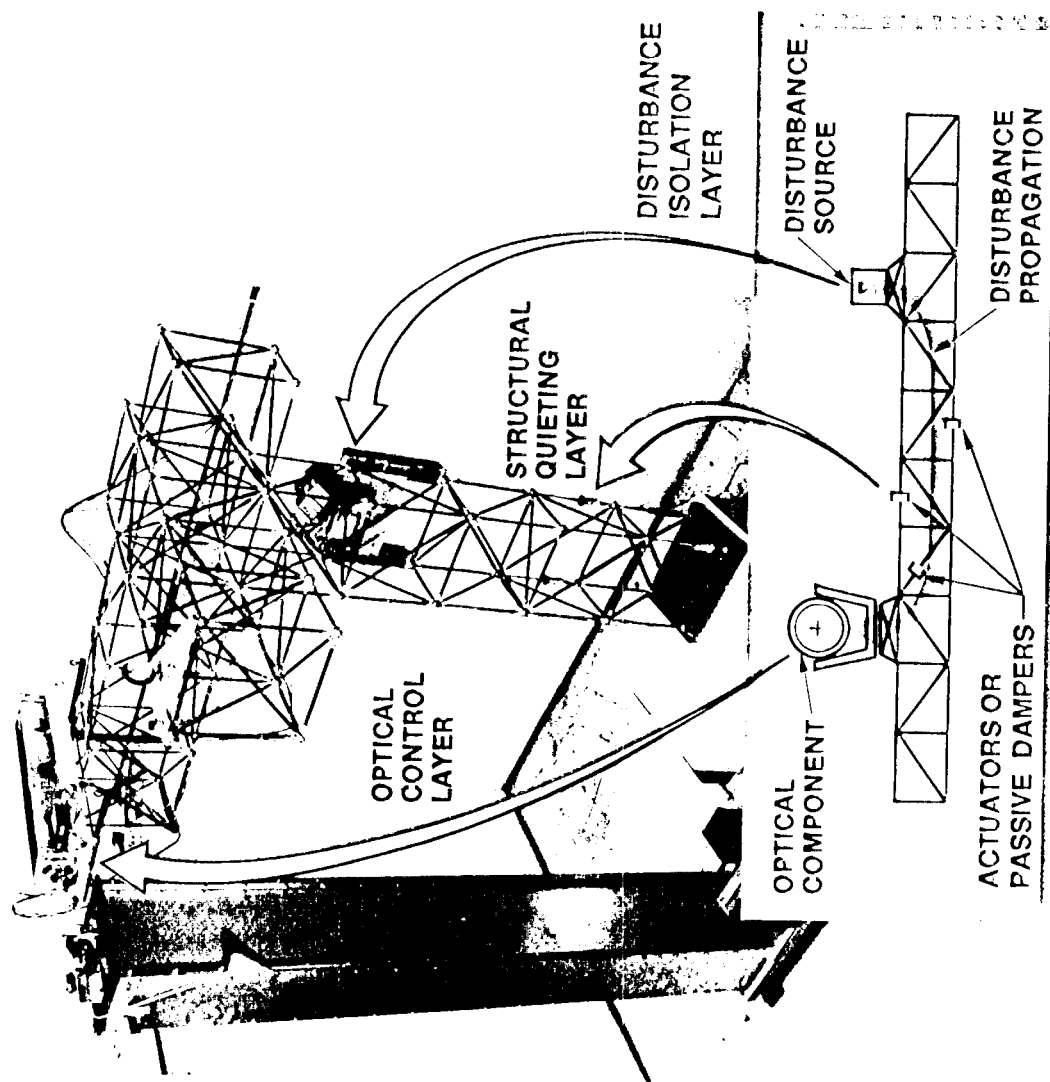
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- A ADAPTIVE STRUCTURES
- B SENSORY STRUCTURES
- c CONTROLLED STRUCTURES
- D ACTIVE STRUCTURES
- E INTELLIGENT STRUCTURES





AMENDMENT

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